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A Practical Guide for Building Collaborations Between Clinical Researchers and Engineers: Lessons Learned From a Multidisciplinary Patient Safety Project

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Objectives: Engineering and operations research have much to contribute to improve patient safety, especially within complex, highly regulated, and constantly evolving hospital environments. Despite new technologies, clinical checklists, and alarm systems, basic challenges persist that impact patient safety, such as how to improve communication between healthcare providers to prevent hospital-acquired complications. Because these collaborations are often new territory for both clinical researchers and engineers, the aim of the study was to prepare research teams that are embarking on similar collaborations regarding common challenges and training needs to anticipate while developing multidisciplinary teams.

Methods: Using a specific patient safety project as a case study, we share lessons learned and research training tools developed in our experience from recent multidisciplinary collaborations between clinical and engineering teams, which included many nonclinical undergraduate and graduate students.

Results: We developed a practical guide to describe anticipated challenges and solutions to consider for developing successful partnerships between engineering and clinical researchers. To address the extensive clinical, regulatory, data collection, and laboratory education needed for orienting multidisciplinary team members to join research projects, we also developed and shared a checklist for project managers as well as the training materials as adaptable resources to facilitate other teams' initiation into these types of collaborations. These resources are appropriate and tailorable for orienting both clinical and nonclinical team members, including faculty and staff as well as undergraduate and graduate students.

Conclusions: We shared a practical guide to prepare teams for new multidisciplinary collaborations between clinicians and engineers.

Key Words: Health care, Hospitals < health care, Behavior < organizational studies, Operations Research and Management Science education < professional, Research and development

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Healthcare is a system ripe with opportunity for engineering researchers to make changes with real-world impact to improve patient safety in collaboration with clinicians.[1,2] To this end, the University of Michigan College of Engineering and Medical School jointly established the Center for Healthcare Engineering and Patient Safety (CHEPS) that aims to improve the safety and quality of healthcare delivery through multidisciplinary, systems engineering-based approaches. The goals of the center are to develop innovative solutions to real-world healthcare problems while simultaneously educating engineering students to prepare them for careers in healthcare delivery. The CHEPS strives to use what Borrego and Newswander[3] call "a truly interdisciplinary approach" in which engineers and clinical collaborators engage in mutualistic learning, resulting in increased understanding of the strengths of each other's fields. The nature of these collaborations, though ultimately beneficial, creates challenges and warrants unique solutions, and these collaborations can be difficult to establish and maintain.[4–7] Because these collaborations are often new territory for both clinical researchers and engineers, the aim of the study is to prepare research teams that are embarking on similar collaborations for common challenges and solutions to consider, as well as training needs to anticipate while developing and managing multidisciplinary teams, particularly when the team includes many nonclinical undergraduate and graduate students.

The M-Safety Lab Research Project

In this article, we will use a project from a recent and ongoing multidisciplinary collaboration initiated in 2015 as a case study to illustrate the common challenges, potential solutions, and training needs for team members that differ by discipline, education, and level of experience. The M-Safety Lab Research Project, a patient safety learning laboratory funded by the Agency for Healthcare Research and Quality,[8] is an example of a multidisciplinary collaboration between CHEPS, health services researchers, human factors engineers, biomedical engineers, computer scientists, physicians, and nurses. The goal of this project is to promote safer care of hospitalized patients by developing and integrating new technologies into a clinical setting. During project development, there was early recognition that developing the new technologies alone would be insufficient; expertise from industrial and

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operations engineers would be necessary to better understand clinicians' workflow and communication needs, both at the bedside and in the electronic medical record. Specifically, strategies would need to avoid adding to the "alarm fatigue" endemic found in many clinical settings and to ensure that the technology is accepted and adopted by clinicians.[9]

Two patient safety issues are being addressed in this project: (*a*) removal of catheters (tubes inserted in the bladder to collect urine or in the veins to administer medication or draw blood) as soon as possible to prevent infections and other complications and (*b*) prompting appropriate strategies to protect skin from developing "pressure injuries" (previously known as pressure ulcers) during hospital admissions from lying in bed.[10–14] Despite technical knowledge of how to prevent these complications, they often still occur. Catheters commonly remain in place for longer than appropriate (increasing infection risk) because of lack of physician awareness of catheter presence and poor communication between nurses and physicians regarding catheter necessity.[15,16] Similarly, physicians and nurses are often unaware that the patient has "at-risk" skin or has already developed a pressure injury.[17,18] In addition, it can be challenging to tailor preventive strategies for patients, as pressure injuries still occur despite routine repositioning of the patient in bed to avoid fragile skin being exposed to high or prolonged pressure.[19,20] The current, flawed system depends on the clinicians to continuously check each patient for such hazards, which are commonly hidden from plain sight. Lastly, both patient safety issues involve many clinicians, including physicians at all levels, advanced providers, nurses, and medical assistants, who need to communicate and coordinate patient care. A multidisciplinary approach was chosen to better understand and develop potential solutions for these two safety issues because these common complications differ with respect to the role each type of clinician has in prevention and the currently available preventive strategies. For example, intervention types to prevent these complications include improving clinician education, mandatory policies regarding catheter and skin care, clinical decision support tools within the electronic medical record, as well as an increasing number of technologic strategies, such as different types of urinary catheters and devices to monitor and modify the pressure experienced by skin.

We began by forming a team that included four physicians with expertise in prevention of catheter and/or skin complications, four engineering faculty members with expertise in human factors, industrial operations, biomedical and mechanical engineering, an intensive care nurse with expertise in nurse-physician communication, a wound care nursing expert, three qualitative data methodologists, and an experienced project manager. To date, this project included 26 CHEPS students, three graduate students outside of CHEPS in mechanical engineering, and a premedical undergraduate student outside of CHEPS. At the time of

matriculation to this project, CHEPS students included 19 undergraduates, three master's degree candidates, two PhD candidates, and a medical student, with backgrounds including nursing, industrial and operations engineering, computer science, biomechanical engineering, environmental engineering, public health, information sciences, and premedical sciences. Several students had backgrounds in several of these fields. The CHEPS involves engineering students of all levels, ranging from undergraduates to doctoral candidates, and borrows from the medical field in creating a "residency for engineers," in which students, closely supervised by faculty, learn by solving real-world problems. Although multidisciplinary coursework in engineering education is common, CHEPS is unique in that it does so outside the rigid structure of a "senior design" or similar "capstone" course.[4,21]

We approached the research project using an iterative process as illustrated in the Figure 1, beginning with "Problem Analysis" to better understand challenges regarding clinician awareness and communication of catheter and skin risk factors and complications in both simulation and clinical settings. To begin the problem analysis phase, the team conducted observations in the clinical setting as well as interviews with clinicians, patients, and families, to better understand the physical environment of the unit, the workflow, team communication, and concerns that would need to be addressed. Our multidisciplinary team has met regularly to discuss findings and design the technologies and workflow strategies. The engineering students have been involved at all phases of this ongoing project, performing observations in the clinical setting for problem analysis, informing development, planning implementation, and are currently actively involved in data collection in the evaluation phases in both the simulation and clinical settings.

The team identified specific barriers to catheter and at-risk skin awareness including the following: pertinent data being hard to find in the electronic medical record, catheters and at-risk skin often physically hidden under bedding and clothes, and sporadic/incomplete communication among clinical team members about catheters and skin.[22] To date, our team is exploring and piloting interventions using different types of technology to improve awareness of catheters and vulnerable skin, including technology that focuses on increasing visibility of catheter and skin data, as well as technology to report patient risk throughout hospitalization.

We ensured that all engineering students participated in hospital unit observations, clinically oriented discussions, and determination of project intervention requirements for the following three reasons: (*a*) this project focuses on both technology development and the human factors associated with ensuring adoption, (*b*) we recognize the value of diversity of viewpoints in solving complex problems in healthcare, and (*c*) CHEPS aims to train students for future work in multidisciplinary environments.[23] Likewise, the clinical team members actively participated in design discussions

FIGURE 1. Research project approach. This figure illustrates the iterative approach applied by our multidisciplinary team for better understanding the problem(s) being targeted for interventions (e.g., problem analysis) and then designing and developing prototype interventions, that are evaluated initially by formative evaluations (in simulation settings) before a summative evaluation by pilot testing in a clinical setting.

and gained exposure to the issues underlying the choice of technology platforms and human factors design principles.

Challenges to Anticipate, Solutions to Consider, and a Checklist With Training Materials for Teams Embarking on Similar Collaborations

In the course of the project described, as well as other recent multidisciplinary projects, we have encountered many challenges that impact successful multidisciplinary collaborations beyond the inherent clinical and technological aspects of the research itself. We outline these below and discuss how we attempted to solve these challenges (Table 1). As several of these challenges relate to differences in education and experience between clinical and engineering team members, we also developed several training materials and a comprehensive checklist of the types of clinical, regulatory, data collection, and laboratory education needed to orient team members that we anticipate will be helpful to both principal investigators and project managers while designing and managing similar collaborative projects (Table 2).

1) **Trust within the team:** When the project began, we were quickly faced with the challenge of building trust and understanding across the group. It was essential that we explicitly recognized the unique strengths, limitations, and differences of each individual and learned how to best leverage the diverse strengths. For example, instead of asking the engineering students to use a clinical observation framework developed by clinical researchers, we benefitted from asking the engineering students what framework they would use to observe a clinical environment. In doing so, we moved toward mutualistic learning and what Borrego & Newswander[3] call "a truly interdisciplinary approach" in which team members aim to ask, "What can we learn from you?" rather than, "What can you do for us?" This focus on reciprocal learning has not only resulted in greater trust between team members but has been immensely beneficial for the engineering students, who have learned more about the clinical environments and professionals with whom they will work throughout their careers.

2) **Trust beyond the team:** Perhaps more challenging than getting acceptance across the team was ensuring that those outside the team, such as nurses whose work would be impacted by our results, were comfortable. This acceptance is critical on the wards, where nurses are focused first and foremost on the well-being of their patients and may be wary of outsiders, especially those with little clinical or clinical research experience. We found it valuable to prepare flyers that included the project's description and goals, an explanation of the team and its members, and photos of those who would be conducting observations in the clinical setting. These flyers were distributed to those who might interact with the team, as well as posted in break rooms and other visible locations in the hospital units in which we worked.

We also recognized that the clinical setting in which our research team works is a risk-averse and highly regulated environment. All tasks performed in this environment that require time, attention, and change in workflow have the potential to distract busy clinicians. With many clinicians experiencing daily task overload, we were sensitive to design our data collection with goals to minimize our presence in the clinical unit as a distraction or additional task to manage. Unfortunately, as well understood in the human factors literature, distractions and task overload in a clinical setting can increase the risk for medical complications, such as errors in medication administration or reduced awareness of a patient's clinical status.

Trust beyond the team is also impacted by the clinical setting's high level of risk averseness because this impacts the pace and complexity of projects due to multiple levels of supervision and approval required for observations and interviews with clinical staff, as well any clinical interventions. These required approvals include not only traditional institutional review board (IRB) approvals but also approval by a nursing committee that reviews all research projects that impact nurses and by nurse and physician leadership within the clinical unit studied. In addition, many other committees are required to approve any intervention that communicates with the electronic medical record and any device that enters a patient room to ensure compliance with hospital policies, patient privacy protections, environmental regulations, and facility safety regulations (Table 2, Section 6).

TABLE 1. Challenges Anticipated in Multidisciplinary Collaborations and Proposed Solutions

Challenge	Solutions
1. Trust within the team	• Alternate meeting locations to mitigate travel burden • Open up common work areas to foster collaboration • Involve engineering students in "clinically focused" meetings and vice-versa to encourage reciprocal learning
2. Trust beyond the team	• Prepare flyer with description of project and team members' roles for hospital units • Solicit feedback from hospital collaborators • Create standardized training curriculum (Table 2) for team that can be disseminated to hospital staff
3. Vernacular language	• Ensure continuous involvement of clinical and nonclinical team members in meetings • Minimize use of domain-specific language and technical jargon during meetings • Create visual aids and glossaries to help students become acclimated with the clinical environment
4. Privacy	• Develop formal training program (Table 2) focused on data security and Health Insurance Portability and Accountability Act compliance
5. Variation in skill sets and expertise	• Maximize face-to-face meeting time • Encourage undergraduate students to lead project meetings
6. Logistical challenges	• Be explicit about expectations from all project team members to help students feel more involved and accountable • Develop a streamlined training curriculum to minimize onboarding time (Table 2) • Appoint a student liaison to take notes and disseminate information to students who cannot attend all project meetings

TABLE 2. Required Training Checklist for Team Members joining Medical Research Projects[+]

Status [++] Task for Completion

1. Ethical Research and Patient Privacy Training[+++]

☐ Complete your institution's training on research ethics and compliance (e.g., Program for Education and Evaluation in Responsible Research and Scholarship (PEERRS) Module(s), or the Collaborative Institutional Training Initiative (CITI Program) training).

☐ Complete your institution's Health Insurance Portability and Accountability Act (HIPAA) Module, and any additional institution-specific permission and documentation requirements (e.g., Without Compensation "WOC" appointment application for Veterans Affairs projects).

☐ Review the project's study protocol that was approved by your institution's Institutional Review Board (IRB), and ensure you have been added to the study protocol.

2. Clinical Environment Training and Requirements

☐ Complete your team's orientation to the clinical environment (e.g., watch the "Orientation to Hospital Projects: Professionalism, Ward Culture, and Mandatories" presentation: http://psep.med.umich.edu/msafetylab.html).

☐ Review the Emergency Code Terminology for the clinical environment you will be entering (example: Emergency Room, ICU, Operating Room).

☐ Review guide regarding common equipment in use in the clinical environment you will be entering (for example: Hospital Unit Guide: http://psep.med.umich.edu/msafetylab.html).

☐ Obtain the required photo identification card required for your institution for visiting clinical settings (note: this may need to be returned at the end of the project).

☐ Complete the "Checklist for Graduating Students Leaving the M-Safety Lab" available at http://psep.med.umich.edu/msafetylab.html.

3. Infection Control Training

☐ Complete Personal Protective Equipment (PPE) In-Person Training with your institution's Infection Prevention Manager. Note: this is similar to education provided by the CDC at: https://www.cdc.gov/hai/prevent/ppe.html but is tailored for the institution and unit of interest.

☐ Complete your institution's hand hygiene training module (e.g., Hand Hygiene for all Healthcare Providers module for University of Michigan employees).

☐ Complete your institution's other Infection Prevention modules (e.g., Standard Precautions, Tuberculosis Precautions, Transmission-based Precautions, Joint Commission Action Plan – Contact Precautions).

4. Immunizations

☐ Obtain and submit proof of receipt of all immunizations or serologic immunity required of volunteers in your institution's hospital(s) where you will be working on this project: e.g., MMR, Tdap, Chicken Pox, TB test, Flu Shot.

5. Team Communication and Schedule Requirements

☐ Electronic contact information (email, mobile, and pager if applicable) exchanged with Project Manager to enable rapid communication about changes and status updates regarding meetings and research visit sessions.

☐ Schedule research visit sessions in pair with another research team member when performing observation or survey visits with research subjects in the clinical setting or simulation center.

6. Training Related to Data Collection and Data Entry

☐ For observation tasks, review the project's orientation materials to observation in qualitative research (e.g., "Use of Observation in Qualitative Research" materials at for example: Hospital Unit Guide: http://psep.med.umich.edu/msafetylab.html), and attend the Project Manager's additional training related to performing observations in the targeted unit, targeted subjects for observation, consenting tasks if applicable, and arrange to shadow an experienced observer.

☐ For survey tasks, meet with the Project Manager to orient you to the particular survey tool, the study protocol for identifying and approaching subjects (and consenting/documenting if applicable by the project), data entry task requirements, and secure destruction of paper tools after data entry.

☐ For assisting with interview or focus group tasks (for our teams, these are led by an expert in qualitative methods), meet with the Project Manager to receive training on the process for performing and documenting the informed consent to interview, audio recording processes if applicable, data entry task requirements, and secure destruction of paper records after data entry.

☐ Complete your institution's training for viewing the electronic medical record for the Research Project.

☐ Complete session with Project Manager to orient you to the database management software that is approved for this project's data collection (e.g., REDCap®), and review of principles for reliable and accurate data entry, including handling of missing data.

☐ Review the expectations and plan for checking in with Project Manager before departing the clinical setting from each data collection visit, to review any unexpected issues and additional needs to address.

☐ FINAL CHECK BEFORE ENTERING THE CLINICAL SETTING OR VIEWING ANY PROJECT DATA: Given all the trainings required, please check with project manager to ensure your trainings have been completed and your addition as a team member to the study protocol has been approved by the IRB.

TABLE 2. *(Continued)*

7. Technology Development/Evaluation Requirements

☐ Review the institution's requirements for types of evaluations and approvals required *in addition to IRB approval* with the Project Manager that are needed for new devices being developed in this project before they can be studied in simulation or the clinical setting with research subjects. The team and/or committee evaluations required for which your role includes facilitating and/or providing documentation to complete are:

☐ Hospital Biomedical Engineering Unit's evaluation and risk assessment	☐ Hospital Quality and Safety Leadership and/or Committee(s)
☐ Environmental Services Team	☐ Nursing Research and Translation Committee
☐ Electronic Medical Record Team(s) involving Data Security & Research Projects	☐ Physician Leadership for Clinical Unit(s) of Interest
☐ Infection Control Leadership and/or Committee	☐ Nurse Leadership for Clinical Unit(s) of Interest
☐ Device Sterilization Committee	☐ Leadership for Clinical Service(s) of Interest
☐ Others:	

☐ Review your role with the Project Manager for developing and updating the new technology's anticipated "Data Safety Monitoring Plan" as the technology evolves from design to final prototype, as well as the "Failure Analysis" report outlining potential anticipated device failures, causes, and measures taken to both monitor, prevent, and address any anticipated device failures.

☐ Review the laboratory data collection and storage requirements with the Engineering faculty leading the engineering laboratory, including a well-annotated research notebook system to document the evolution of the device's development for IP purposes. This can be a physical lab notebook or an electronic lab notebook system (e.g., https://guides.lib.umich.edu/ern), but one or the other must be used. Any software code should also be well annotated in order to ensure a smooth transition to new engineers joining the team when graduating students depart.

☐ Check with the Engineering faculty what official and unofficial training you will need from the University to work in their laboratory (e.g., https://ehs.umich.edu/education/what-training-do-i-need/ and at minimum this involves a basic laboratory safety course such as "BLS025W General Laboratory Safety Training"). Ask the Engineering faculty what other forms of training you need to use any equipment in their labs (e.g, if you need to use machine tools, you will need to wear appropriate clothing, ensure long hair cannot get caught in the machinery, and never work alone).

☐ Review the project's requirements and opportunities related to Intellectual Property (IP) developed in this project with the Project Manager (e.g., "Reminders about Intellectual Property for the M-Safety Lab Research Project" at https://psep.med.umich.edu/msafetylab.html). For engineering students involved in new device development for this project, also review the opportunity and responsibilities as co-inventors with the Principal Investigator and the lead Engineering faculty involved in the device's design and development, and conflict of interest disclosures. Broadly speaking if the project is funded by a research contract funded through the University, then the University owns the IP related to any invention, even if you are a named inventor on any patent that results.

[+]All training resources developed specifically for this project are available at: https://psep.med.umich.edu/msafetylab.html.

[++]Based on your specific role in the project, the Project Manager will assess which of these are required to be completed, or could be designated as not applicable. Section 1 will be required of all Team Members; sections 2-5 will be required for all team members who will be performing any tasks within clinical settings. Sections 6-7 will be assigned based on your individual role within the project.

[+++]If the study involves data collection from multiple clinical locations (such as an academic medical center and a Veterans Affairs hospital), there will often be different IRBs and requirements related to research ethics/compliance and infection control training, and data storage. Each team member should clarify with the Project Manager what is required for the specific clinical sites/data you will be working with on this project.

To help improve comfort of the clinicians with our research team and to reduce the risks our team could bring to the clinical ward, we developed a comprehensive training curriculum and list of requirements for team members going into the clinical environment (Table 2). Staff from across the hospital were consulted in developing the curriculum's components related to clinical orientation and infection control (Table 2, Sections 2–4), which we then conveyed to nurse zleadership and disseminated to nurses on the unit to help them feel more comfortable with our presence. Requirements included infection control training; documentation of all pertinent immunizations; ethical research training; and a presentation, given by a critical care physician with decades of experience orienting medical students to the hospital at our Medical School and an intensive care unit nurse, titled: Orientation to Hospital Projects: Professionalism, Ward Culture, and Mandatories (available online at http://psep.med.umich.edu/msafetylab.html).

We found that the development of a standardized training curriculum was also helpful for students, who acquired a base of knowledge surrounding the importance of protecting personal health information and following infection prevention protocols while on the wards. This helped students feel more comfortable when observing in the hospital and collecting project data. Moreover, the curriculum has helped to streamline a previously time-consuming onboarding process for new students, allowing them to contribute to the project much more quickly.

Most importantly, the nurses and others involved in our observations were encouraged to provide their insights, potential solutions, and their concerns about the project. This continuous solicitation of feedback was conducted not only during observations, but also during nurse team meetings, which we repeatedly attended to garner critiques and gain the unit's trust.

3) **Vernacular language:** Both of the above issues of trust are largely grounded in fear. Some of this is tied to fear of being able to do one's job well, whether it be the students wanting to perform well academically, the clinical research team wanting successful research outcomes and future success in publication and grant writing, or practicing nurses being concerned not only with their patients' well-being but also with their personal autonomy and experience at work. In addition, we found an innate and universal fear that is somewhat related to the well-known "impostor syndrome." Because of the multidisciplinary nature of the team, it was easy to feel ignorant and then to be reluctant to contribute.[24,25] However,

by ensuring continuous involvement of both engineering and clinical team members in project meetings, we sought instead to embrace the new perspectives that engineers and engineering students provided. We have found fostering a meeting milieu in which students feel comfortable speaking up to be crucial in this process. In addition to emphasizing the inherent strengths of each team member and the value of bringing together diverse backgrounds, we focused on the importance of minimizing the use of domain-specific language, technical jargon, abbreviations, and other barriers to clear communication. Even the simple acknowledgement that one's terminology might be unfamiliar to others on the team can be helpful in reducing the building of barriers.[2,7] In addition, we have found the use of aids, such as analogies, visuals, and glossaries (Table 2, Section 3, available online at http://psep.med.umich.edu/msafetylab.html) to be especially helpful in bridging terminology gaps. For instance, at the onset of the project, an engineering student was tasked with researching common pieces of equipment and technology used in intensive care units, and creating a visual glossary that future students could use as a reference, which has been continuously added to and is reviewed by all students during the onboarding process. We have also attempted to leverage the team's diverse set of "languages." One such example has been using computer science students as "interpreters" for our clinical team members when meeting with representatives from our institution's electronic medical record team and discussing technical requirements for one proposed technical intervention.

4) **Privacy:** In the healthcare environment, patient privacy is of paramount importance. Privacy concerns are a major source of potential distrust for the clinicians, who must feel confident that the students, especially those coming from nonclinical backgrounds, are fully qualified and prepared to handle highly sensitive data. We therefore required team members to complete a formal training program for learning about Health Insurance Portability and Accountability Act of 1996 compliance and other issues associated with data sensitivity (Table 2, Section 1). This is not only beneficial for the students in ensuring that they are properly trained, but it also provides us with the means to demonstrate to our hospital collaborators *how* the students are trained and to build their trust in the thoroughness of our process and our commitment to ensuring full compliance. We shared our training program with nursing leadership on the units with which we worked and solicited feedback.

5) **Variation in skill sets and expertise:** We benefit from the diverse knowledge of our team members, but this also introduces potential challenges in reaching consensus and mutual trust. Moreover, clinicians are often unaware of the skills that engineers and, in particular, engineering students can bring to a project team. We have therefore found it critically important to have as much face-to-face time as possible, both as a full team and in small (but still cross-disciplinary) subgroups. When the work is partitioned across disciplines, much is lost.[3] Maintaining a diverse group in all discussions has proven invaluable to our success. This has also given each individual the chance to play both a leadership role and a following in different instances. For example, an undergraduate engineering student may need to ask many questions and be given significant guidance to understand the physiological issues underlying the problem at hand, but then later gain confidence in taking the lead in explaining issues associated with deciding on a technology platform. We also needed to standardize the

education and orientation of students regarding research data collection (including qualitative data collection by observation, surveys, and interviews), data entry, and data storage, intellectual property development and protection, as well as orientation by engineering faculty to those working within the engineering laboratory for prototype development (Table 2, Sections 6–7).

6) **Logistical challenges:** An important feature of our projects is that like most real-world problems studied and solved, they require a team to work over multiple years, involving multiple cohorts of engineering students and other research assistants working over multiple semesters. The longitudinal aspect gives the CHEPS students a different experience than a project limited in scope and time, requiring the project manager and principal investigator to quickly orient new cohorts of team members to project goals, priorities, and skills needed, as well as to be meticulous in documentation to smoothly transition the project to the next cohort of students. Thus, a comprehensive checklist and training curriculum was developed (Table 2), which we share as adaptable resources to facilitate other teams' initiation into these types of projects.

We have also found that among the most daunting challenges associated with involving students heavily in project teams led by professionals is student timelines, with students often joining and leaving the project team at the end of the academic year and having varying work capacity depending on the time of year. These scheduling challenges have impacted the project both on a macro scale (i.e., setting long-term goals), as well as on a micro scale (i.e., scheduling individual meetings).

In terms of individual meetings, it has been valuable to provide frequent reminders to the staff and clinicians about the scheduling limitations faced by the students, who have limited control over their class schedules and limited time available to spend on the project. Likewise, the students have benefited from being reminded of the more traditional schedule of the faculty and staff. Even simple gestures, such as establishing that a 7:00 a.m. meeting might be problematic for students, as they may have been working late on schoolwork the previous night, and likewise that a 7:00 p.m. meeting might be problematic for faculty or staff because of childcare needs, has helped everyone to be reminded that the other members are human. We have found that alternating meeting locations between engineering and medical campuses has helped mitigate excessive travel burden on any one group and has reinforced the essentiality of both engineering and clinical collaborators to the project. Furthermore, engineering and clinical team members have opened up work space within their respective buildings to foster continued collaboration.

However, despite our strategy to alternate meeting locations, we have continued to find it difficult to have frequent full-team meetings. To circumvent this issue, we have found it useful to appoint a student lead, who has more availability and acts as a liaison between the other students who might not all be able to make all meetings and the rest of the group. This liaison meets more frequently with the other students to keep them up to speed and solicit their ideas, which can then be passed on to the rest of the group. Frequent meetings with project subteams, thorough note-taking during meetings, and the establishment of concrete action items with deadlines and task ownership have also proved to be useful in keeping students engaged with the project, despite their hectic schedules.

On a larger scale, to overcome students joining and leaving the project at the end of the academic year, we have learned that being explicit with expectations from students and faculty members in terms of timelines, work capacity, and length of time available to be involved with the project helps students to feel more accountable for project outcomes. We have also initiated a concerted effort as a group to increase the amount of work performed during the summer, when students work full time at CHEPS and have the greatest amount of time available for the project.

DISCUSSION

Prior literature involving multidisciplinary teams has focused on better defining interdisciplinary research,[26] organizational and team factors that contribute to effective interdisciplinary research teams[6,7,27] and on the risks and benefits of engaging in interdisciplinary teamwork.[5,6,27,28] For instance, Weaver[27] outlines antecedents, such as having the right team of experts with a dedicated leader, the importance of the physical environment, and institutional conduciveness to interdisciplinary work; processes, such as team member maturity and flexibility regarding their knowledge base, relationship building, and publications; and outcomes, such as development of novel ideals, integrative models, and institutional changes, that contribute to effective transdisciplinary scientific collaboration. Thompson,[7] meanwhile, identified factors that build "collective communication competence" in interdisciplinary teams, including spending time together, practicing trust, discussing language differences, and demonstrating presence. Korb et al[5] discussed solving challenges associated with interdisciplinary teams working in surgical device development and stress the importance of developing shared mental models, common goals, clear delineation of responsibilities, and encouraging a culture of cooperative learning. In comparison, our study builds on prior literature in three major ways, and we provide a case study in which we implemented many of the factors identified by past research as being essential to the success of multidisciplinary teams, including spending time together, discussing language differences, and clearly delineating responsibilities.[5,7] Second, we identify factors unique to building effective interdisciplinary teams involving industrial engineers and, in particular, engineering students. Third, we build from frameworks that have been well established in the literature to offer concrete suggestions and strategies to mitigate challenges and facilitate the creation of effective multidisciplinary teams involving engineering students and healthcare professionals (Table 1). Furthermore, which we feel will be most helpful to other researchers, we developed and shared a practical guide including an extensive checklist and training materials for anticipating and addressing the extensive clinical, regulatory, data collection, and laboratory education needed for orienting multidisciplinary team members to join similar research projects (Table 2).

The M-Safety Lab Research Project we shared as a case study has reaffirmed to us the usefulness of an interdisciplinary team while tackling patient safety challenges, despite the many challenges associated with collaborating across disciplines and education level. In particular, CHEPS engineering and computer science students have been crucial components of the project team by contributing ideas, collecting data, and helping develop and implement technological solutions. They have also benefitted from the interdisciplinary nature of the project, gaining further knowledge in the healthcare realm relevant to not only healthcare delivery systems, but also to patient data privacy, infection prevention protocols, and professionalism on hospital wards.

However, despite the multitude of benefits, the project has faced growing pains associated with interdisciplinary teams, such as gaining trust between team members, gaining the trust of hospital collaborators, language and jargon differences, data privacy, wide variation in expertise, and logistical challenges associated with coordination between a large number of professionals and students. In response, we have developed and shared a number of strategies to address these issues as they arise, the most important being the development of a comprehensive training curriculum[29] for research team members and the continued fostering of a team culture that stresses the cruciality of interdisciplinary perspectives in addressing complex healthcare issues.

CONCLUSIONS

Given the complexity of the healthcare environment in which patient safety issues have persisted, multidisciplinary collaborations between clinicians and engineers are a critical approach for developing and evaluating novel solutions, particularly those that involve new technologies. Building and managing such teams can be daunting while also immensely fruitful, and we hope the lessons and strategies shared, as well as pragmatic and adaptable resources for orienting new research members, will encourage other researchers to embark on these types of collaborations.

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